Thermal Study of Inverter Components

N. Robert Sorensen[1], Edward V. Thomas[1], Michael A. Quintana[1], Steven Barkaszi[2], and Andrew Rosenthal[3]
[1]Sandia National Laboratories, Albuquerque, New Mexico, USA
[2]Florida Solar Energy Center, Cocoa, Florida, USA
[3] New Mexico State University, Las Cruces, New Mexico, USA

ABSTRACT

Thermal histories of inverter components were collected from operating inverters from several manufacturers. The data were analyzed to determine thermal profiles and to assess the effect on inverter reliability. Thermal profiles were shown to follow diurnal and annual cycles. An accumulated damage model was applied to the temperature profiles and an example of using these data to predict reliability was explored.

BACKGROUND

Sandia National Laboratories (Sandia) has a long history evaluating the reliability of photovoltaic (PV) systems. Inverters are an integral part of the PV system and must function properly for the system to be operative. Fans and heat sinks are employed to mitigate heating of components in an attempt to improve long-term reliability. It is thought that knowledge of the thermal history of individual components (capacitors, IGBTs, transformers, circuit boards, heat sinks, etc.) may be useful in assessing system reliability.

TEMPERATURE MEASUREMENT

Several inverters were instrumented with thermocouples to monitor the temperature of individual inverter components. Four-channel data loggers were used to record the temperature of three components and the internal ambient for each of the inverters. Data were collected at 30 second intervals, and then filtered to provide 10 minute measurements. The data were downloaded from the data loggers on a monthly basis for analysis.

Figure 1 shows temperature profiles for one inverter during the month of July. The components included in this data set are a capacitor, the IGBT control board, and the transformer. In addition, a thermocouple recorded the temperature in the enclosure (Upper Ambient). An internal reference in the data logger also recorded the ambient temperature. As seen in Figure 1, the highest temperatures were recorded for the IGBT control board and the transformer. The maximum temperature recorded was around 60C. The diurnal nature of the temperature profile is obvious. Components heat up during the day and cool down at night. However, it is interesting to note that, while the temperature of the capacitor and transformer approached ambient at night, the IGBT control board did not.

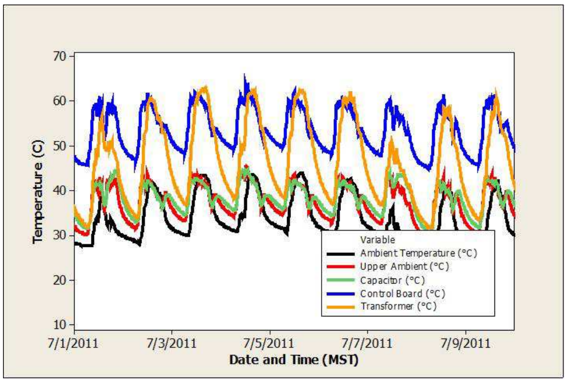

Figure 1. Temperature profiles obtained during the month of July. The three instrumented components included the capacitor, IGBT control board, and transformer.

The data can be used to generate an empirical CDF file as shown in Figure 2. In this type of plot the overall temperature can be evaluated. Data are included for both January and July, as well as the accumulated time. The solid curve represents overall results. The dashed lines are for the individual months. From these plots, a definite seasonal influence can be seen. As expected, there is a significant shift of the CDF to higher temperatures for the month of July.

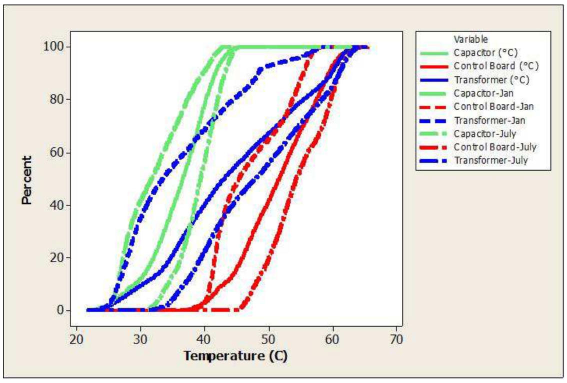

Figure 2. Empirical CDF profiles for the three instrumented components during the months of January and July. The dashed curves represent measurements taken in January.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Figure 3 presents temperature distributions for the three components and the ambient for the month of January. Consistent with the temperature profiles, the IGBT control board shows no history of low temperatures, indicating that it remains warm, even during periods of non-operation. In contrast, the transformer and capacitor temperatures include the range for the ambient temperature. Note that the transformer and IGBT control board exhibit temperatures considerably higher than either the ambient or the capacitor.

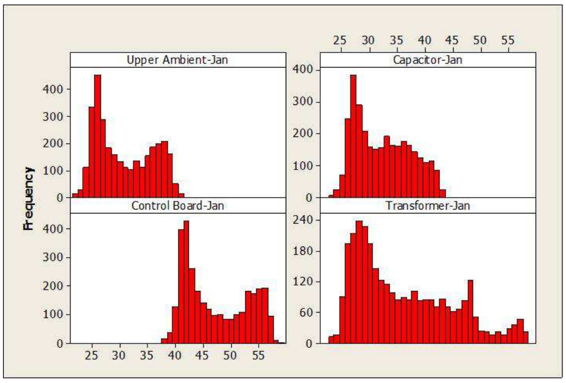

Figure 3. Thermal profile (distribution) for the month of January.

ACCUMULATED DAMAGE MODEL

Given these data and assuming a thermally-activated degradation mechanism, we would like to know the failure-time distribution over a varying temperature profile. In order to do that, information about the activation energy must be known. To demonstrate the process, we can assume that the activation energy is known. We can then use a cumulative exposure model with the environmental data taken from the inverters to evaluate the failure-time distribution. The cumulative exposure model assumes that an increment of degradation occurs during each increment of time, and depends on the temperature during that time increment. In practice, accelerated aging tests over a range of temperatures are needed to establish activation energies.

The failure-time distribution function is an exponential containing the degradation rate at a given temperature (T) and time (t), given by:

$$F(t;T) = 1 - \exp[-\lambda(T) \times t]$$

where λ is the incremental degradation. It is given by:

$$\lambda(T) = A \times \exp\left[\frac{-E_a / R}{T}\right]$$

where E_a is the activation energy and R is the universal gas constant (Nelson, 2004, pp 83-85).

The cumulative exposure model can be used to express the total damage:

$$\varepsilon = \Delta_{T(1)} \times \lambda_{T(1)} + \Delta_{T(2)} \times \lambda_{T(2)} + \ldots + \Delta_{T(n)} \times \lambda_{T(n)}$$

where $\Delta_{T(i)}$ represents time at temperature *T(i)*, and $\lambda_{T(i)}$ represents the degradation rate at that temperature interval. The incremental damage for each interval ($\lambda_{T(i)}$) depends on *T(i)* through the Arrhenius equation (Nelson, 2004, pp. 501).

We can use the above equations to predict a hypothetical failure probability for an inverter. Assume that MTTF is 5000 hours at 55C. From the first equation, λ(T) is 0.0002 at 328K (MTTF = 1/λ). Assume that E_a/R is 6000K (it might vary from 3000K to 12,000K). Plugging those values into the second equation gives:

0.0002 = *A*·*exp*(-6000/328)

which provides a value of 1.76X10^4 for the activation energy, *A*.

Figure 4 shows the cumulative distribution function (CDF) for an inverter with all of the data collected to date. The data set contains 2481 intervals of 10 minutes each. We can assume that the CDF is representative of the distribution of temperature throughout the whole year. We can now calculate the damage for each time step and use that to calculate reliability for the inverter, based on the exponential given in the second equation.

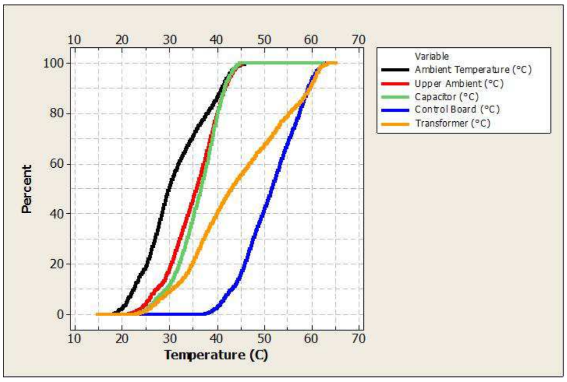

Figure 4. Empirical CDF curves for components instrumented with thermocouples.

Figure 5 shows the predicted probability of failure for the transformer, IGBT control board and capacitor. These curves are based on the assumption of 5000 hours for a mean time to failure, and an activation energy (E_a/R) of 6000K. In this case, the control board, which had the highest cumulative temperature, is the most likely component to fail, followed by the transformer and the capacitor.

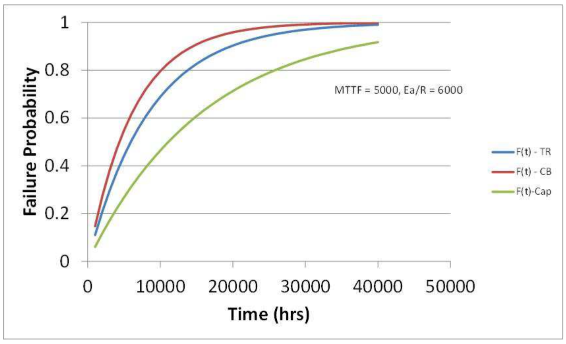

Figure 5. Failure probability curves using an activation energy (E_a/R) of 6000K, and a MTTF value of 5000 hours for all three components.

We can evaluate other failure mechanisms by allowing individual components to have unique MTTF values and/or activation energies. Figure 6 and Figure 7 show how the failure probability curves vary for alternate values of MTTF for the three components. As seen in Figure 7, lowering the MTTF for capacitors to 2000 hours results in the capacitors becoming the life-limiting component. Clearly, these techniques can be used to perform trade-off studies in assessing system reliability. They also suggest that accelerated testing of individual components can be used to generate higher fidelity reliability predictions.

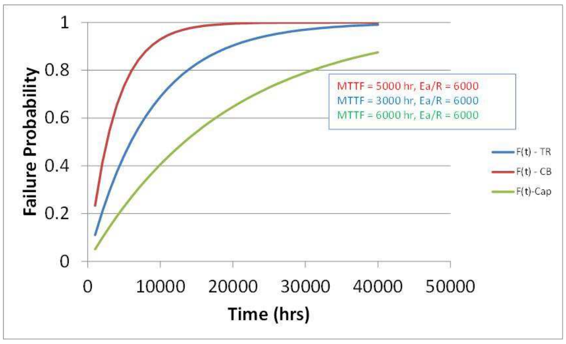

Figure 6. Failure probability curves using an activation energy (E_a/R) of 6000K, and MTTF values of 5000, 3000, and 6000 hr for the transformer, IGBT control board and capacitor, respectively.

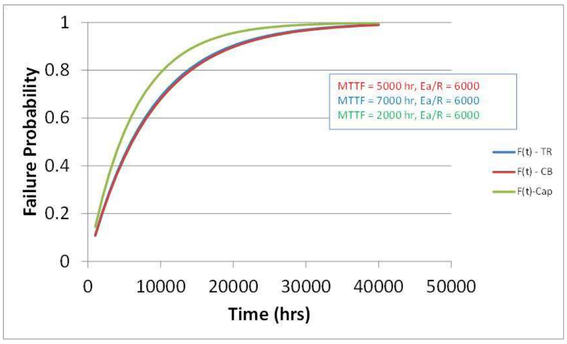

Figure 7. Failure probability curves using an activation energy (E_a/R) of 6000K, and changing the MTTF value for the IGBT control board.

SUMMARY

We have demonstrated how temperature profiles from inverter components can be analyzed to provide insight into inverter reliability. By assuming values of mean time to failure and activation energies for the individual components, the results can be used to predict reliability (probability of failure).

REFERENCES

[1] Wayne Nelson, *Accelerated Testing: statistical models, test plans and data analysis,* Wiley-Interscience, 2004.